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Experimental study on forced thermoacoustic oscillation driven by loudspeaker

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ABSTRACT

Onset and damping temperatures are important characteristics for thermoacoustic engine which decide the level of low grade thermal energy that can be utilized. Using loudspeaker to drive thermoacoustic engine is an effective method to decrease the onset temperature. In this paper, the onset process of forced oscillation driven by loudspeaker was investigated comparing with that of self-excited oscillation. Impacts of driving frequency and power on onset temperature were discussed. The results show that forced oscillation has a higher selectivity for driving frequency. The self-excited oscillation frequency (fundamental frequency) is the optimal choice to drive thermoacoustic engine in practical application. The lowest onset temperature was gradually achieved with the increase of driving power. Pressure amplitude is mainly affected by the onset temperature. The lower the onset temperature is, the smaller the pressure amplitude is. This work provides a guide for the selection of driving signal in practical application.

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1. Introduction

Thermoacoustic engine is a new type of energy conversion device, which can convert heat into acoustic power based on the thermoacoustic effect. With the advantages of simple construction, stable operation and no harm to environment, it attracts lots of researchers' attention. The theory of thermoacoustic has a great progress in recent decades [1–7]. In addition, thermoacoustic engine has been applied in waste heat recovery [8], wind power exploitation [9] and solar energy utilization [10]. Onset and damping temperatures are important characteristics for thermoacoustic engine. Lower onset temperature can make thermoacoustic engine have better utilization of low grade thermal energy. There are many factors that affect the onset and damping temperatures of thermoacoustic engine, such as structural parameter, working medium and method of heating. Wang et al. [11,12] investigated the effect of Gedeon streaming and Helmholtz resonator on the onset and damping processes of thermoacoustic engine. Based on thermodynamics analysis, Qiu et al. [13] developed a physical model to simulate the onset characteristic of a standing wave thermoacoustic engine. To improve the efficiency of thermoacoustic engine, Hu et al. [14] demonstrated that the inevitable viscous dissipation in resonator was the main factor to affect the thermal efficiency and energy conversion. Standing wave thermoacoustic engine might have better performance than traveling wave thermoacoustic engine to achieve higher power density and higher pressure ratio. Yu and Jaworski [15] paid attention on the impact of acoustic impedance and flow resistance on the power output capacity. Particle swarm optimization method was firstly used by Chaitou to optimize the exergetic efficiency of thermoacoustic engine [16]. Parameters such as the stack's hydraulic radius, the stack's position in the resonator and the traveling–standing-wave ratio were taken into consideration. In addition, the influences of stack geometry, resonator length and working fluid on the performance of thermoacoustic engine were also been studied [17,18]. To better utilize the low grade thermal energy, a novel thermoacoustic regenerator using multi-temperature heat sources has been established by Qiu et al. [19,20], which construction can well increase the efficiency of thermoacoustic engine by improving the temperature gradient of regenerator.

Pressure disturbance is an effective method to decrease the onset temperature of thermoacoustic system. Sun et al. [21,22] firstly proposed this method and experimentally decreased the onset temperature of a hybrid thermoacoustic engine from 219 °C to 193 °C by charging and discharging the working gas. Using loudspeaker to drive the thermoacoustic engine is another simple and practical method to bring the pressure disturbance, especially for the open thermoacoustic system. Wang et al. [23] experimentally demonstrated that forced thermoacoustic oscillation had a lower onset temperature than self-excited oscillation. As a useful method to decrease the onset temperature, forced oscillation driven by loudspeaker makes thermoacoustic technique have a further application in waste heat recovery. However, the research about forced thermoacoustic oscillation is insufficient. How the driving frequency and sound power of loudspeaker affect the thermoacoustic onset process is unclear. There has no guidance for the selection of appropriate driving signal in practical application. To

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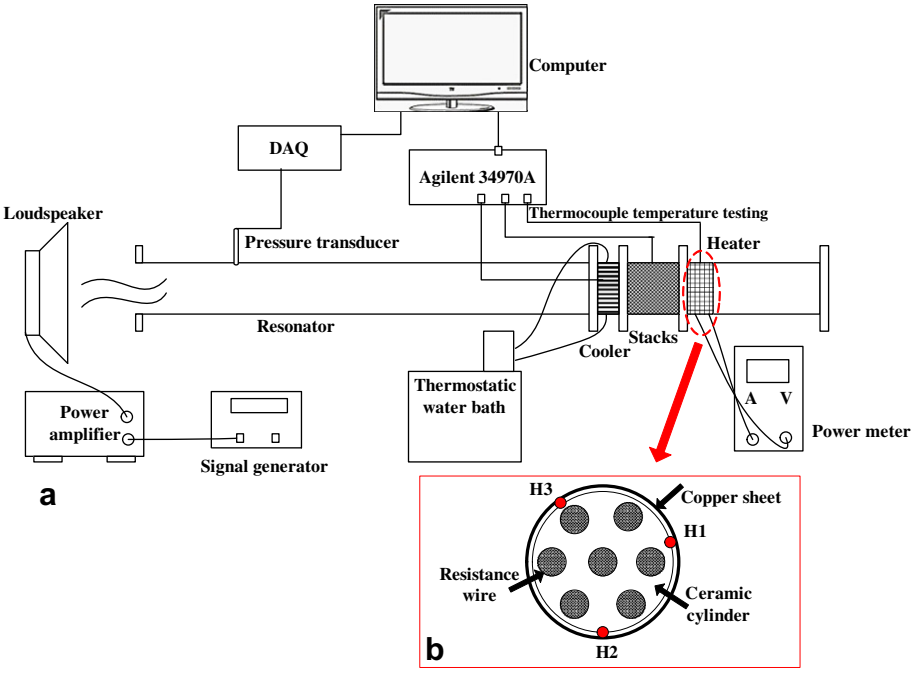

Fig. 1. Schematic diagram of experiment system.

solve this problem, forced thermoacoustic oscillation driven by loudspeaker was studied in this paper. The impacts of driving frequency and power on onset temperature and pressure amplitude were discussed. What is more, to better understand the mechanism of forced oscillation, frequency spectrum analysis was used to compare the onset processes of self-excited oscillation and forced oscillation.

2. Experimental apparatus

As shown in Fig. 1, the thermoacoustic engine in this experiment is composed of heater, cooler, stacks and resonance tube. The structure and dimension of each component have been described in detail in the previous work [24]. The difference is that thermoacoustic core between heater and cooler used in this experiment was made into stainless tube filled with stacks. A porous ceramic cylinder was used as the stack which can realize the irreversible thermal contact between gas and solid. The heater was handcrafted that inserting resistance wires into ceramic cylinder, as shown in Fig. 1b. The surface of ceramic cylinder was covered with copper sheet to equalize the temperature. Electrical heating method was used and the heating power was controlled by voltage regulator and measured by a power meter. Three K-type thermocouples were fixed in the heater to monitor the inside temperature, which were respectively marked as H1, H2 and H3 in Fig. 1b. Since the distances from thermocouples to the heating resistance wires are different, their measured results have a little difference. The average temperature of them is taken as the effective temperature of heater. To better show the performance of heater, temperature change of heater with different heating powers is shown in Fig. 2. The cooler is a tubular heat exchanger that cooled by 10 °C circulating water. Homogeneous copper sheets with space of 1 mm were inserted inside a 20 mm tube as heat exchanger element. Two thermocouples were placed between the copper sheets to measure the temperature. Similarly, the average value of L1 and L2 is taken as the effective temperature of cooler. Temperature data were collected by Agilent 34970A and recorded by computer. The measurement error of thermocouple is ±1 °C in the temperature range −40 to 500 °C.

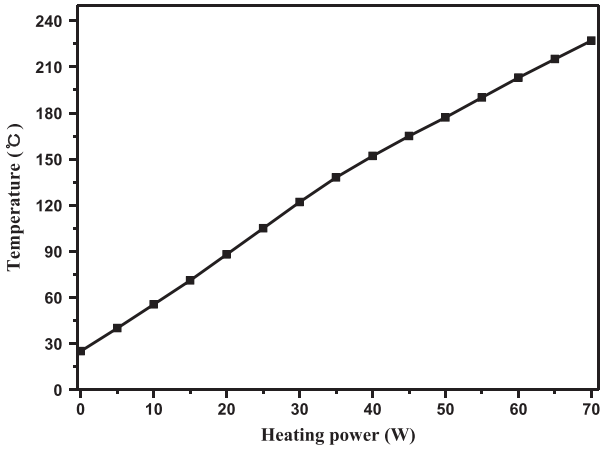

Fig. 2. Temperature of heater versus electrical heating power.

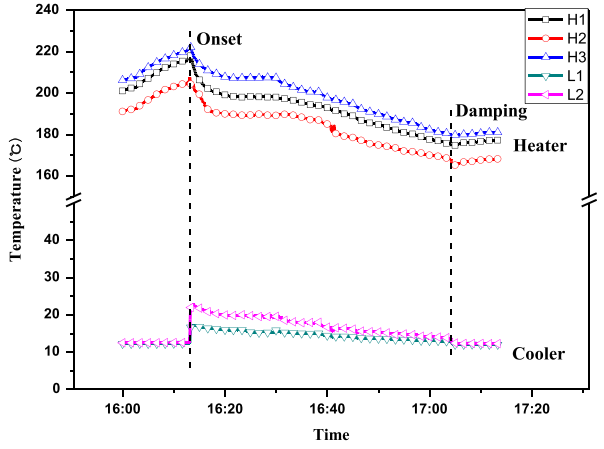

Fig. 3. Onset and damping processes of self-excited thermoacoustic oscillation.

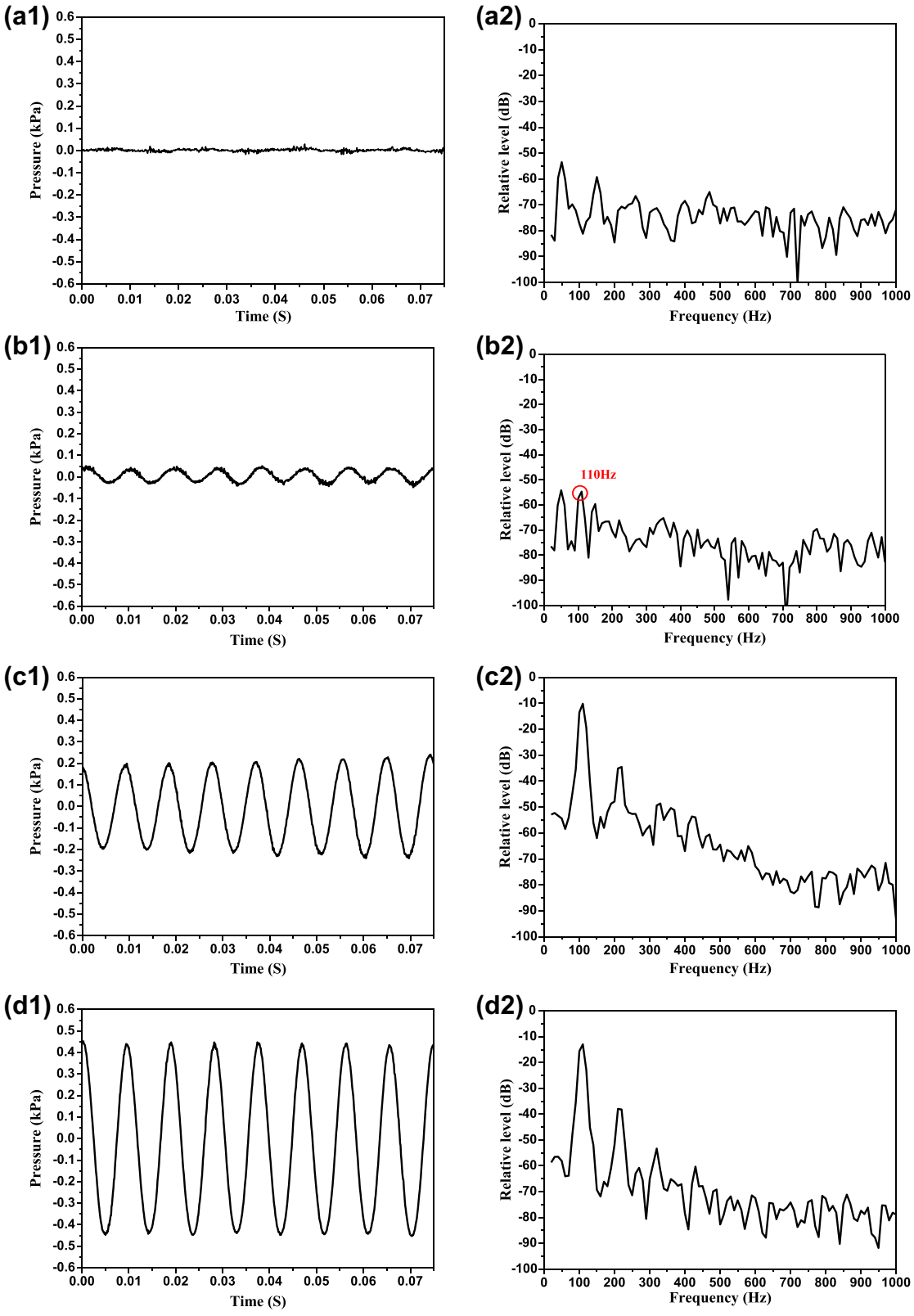

Fig. 4. Pressure and frequency spectrum changes in self-excited onset process.

A pressure transducer was equipped on the resonance tube to observe the pressure oscillation. And the pressure data were processed by self-compiling software based on LabView which can display the pressure waveform and frequency spectrogram synchronously. The uncertainty of pressure data including the measurement error of pressure transducer and data acquisition system is 0.5%. To decrease the onset temperature, a loudspeaker (HiVi SS12) was placed at the open end of resonance tube to drive the thermoacoustic engine, as shown in Fig. 1. It cannot be placed too close to the open end otherwise the work mode of thermoacou-

stic engine will be affected. Meanwhile, it can also not be placed too far from the open end which will cause lots of acoustic loss. In this experiment, the loudspeaker was placed 12 cm away from the open end. The sound signal was generated by a signal generator (RIGOL DG1022) which can adjust the driving frequency of loudspeaker. The sound power was controlled by a power amplifier (B-Audio MARCH-503K) and measured by power meter.

In this experiment, the onset and damping temperatures of self-excited oscillation without loudspeaker (for better comparison, loudspeaker was also placed at the open end without turning on) were firstly measured. The fundamental frequency and pressure amplitude were recorded. Then turn on the loudspeaker and provide it a sound signal, gradually increase the heating power to search the onset temperature of forced thermoacoustic oscillation. Record the pressure amplitude when the oscillation stabilizes and then gradually decrease the heating power to search the damping temperature. Repeat the same experiment process with different driving frequencies and sound powers to study the effect of different driving signals on forced thermoacoustic oscillation. To reduce the measurement error, each experiment point was conducted twice and the average value was calculated as the effective result.

3. Results and discussion

3.1. Self-excited thermoacoustic oscillation

To compare with the results of forced oscillation, self-excited oscillation of thermoacoustic engine without loudspeaker driving was firstly investigated. The temperature changes of heater and cooler during the onset and damping processes are shown in Fig. 3. H1, H2 and H3 respectively represent the temperature of heater in different positions, as shown in Fig. 1b. It can be seen from Fig. 3 that thermoacoustic engine started oscillation when the temperature of heater increased to 215.7 °C. With the onset of thermoacoustic system, heat was converted to acoustic energy. And the heater had a prominent temperature drop. Meanwhile, the cooler had a temperature rise. Then gradually decrease the heating power, system suddenly damped when the temperature decreased to 198 °C. It has a temperature difference of 18 °C between the onset and damping temperatures, which is conducive to utilize the low grade thermal energy as heat source.

As shown in Fig. 4, the onset process of self-excited oscillation was investigated through the pressure variation and frequency spectrum analysis. Logarithm amplitude spectrum was used in the spectrum analysis. The value of vertical axis is calculated by doing logarithm operation to pressure amplitude. This transformation is helpful to observe the periodical signal that covered in low amplitude noise. The formation of pressure waveform is shown from a1 to d1 and the frequency spectrogram of corresponding moment is shown from a2 to d2 in Fig. 4. It can be seen from Fig. 4a that there had almost no pressure oscillation before onset. The frequency mainly distributed at 50 Hz which is the mains frequency. At the beginning of onset, the system had a frequency selection process. The pressure waveform with 110 Hz finally generated, as shown in Fig. 4b. Then the pressure oscillation with frequency of 110 Hz rapidly grew up and 110 Hz became the dominant frequency in frequency spectrogram (Fig. 4c). Finally pressure oscillation stabilized with the amplitude of 0.45 kPa as shown in Fig. 4d. It can also be found that higher harmonic with frequency of 210 Hz and 320 Hz existed in the frequency spectrogram due to the nonlinearity of thermoacoustic oscillation. However, the higher harmonic was very weak which almost had no impact on the pressure waveform. The onset process of standing wave thermoacoustic engine in this work is in accord with the results about hybrid thermoacoustic engine done by Liu et al. [25], who classified the onset process into three stages including energy storing, onset and saturation stage. The onset process of traveling wave thermoacoustic cooler has been investigated by Sakamoto and Watanabe [26], and the results are similar to that of standing wave and hybrid thermoacoustic engine. It can be concluded that whichever types of thermoacoustic engines have the similar onset process. However, they have different oscillation modes and acoustic power output locations after onset due to their different structures.

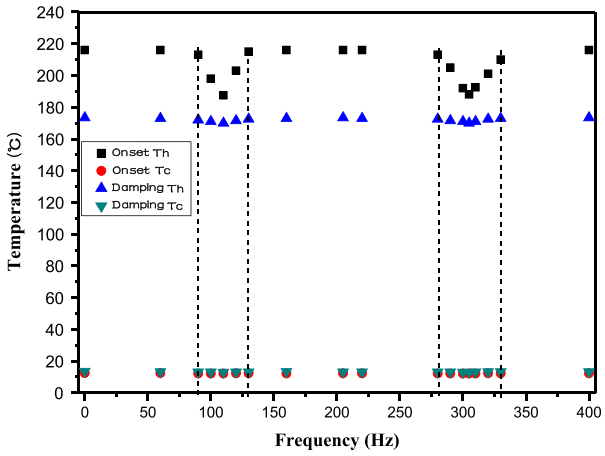

Fig. 5. Onset and damping temperatures with different driving frequencies.

3.2. Forced thermoacoustic oscillation with different driving frequencies

For the selection of effective driving signal in practical application, forced thermoacoustic oscillation was studied under different driving frequencies and driving powers. The effect of driving frequency on the onset and damping temperatures of forced thermoacoustic oscillation is shown in Fig. 5. The driving power was selected as 20 W in this experiment. For the convenience of comparison, temperature point of 0 Hz represents the situation of self-excited oscillation in Fig. 5. It can be seen that onset temperature decreased from 215.7 °C with 0 Hz to 187.5 °C with 110 Hz driving frequency which is the self-excited oscillation frequency (fundamental frequency). When the driving frequency was between 90 Hz and 130 Hz, the onset temperature also had a decrease although it was not as significant as that of 110 Hz. Thus we can define this interval as the effective frequency range, in which the onset temperature can be effectively decreased. The second effective frequency range appeared in the vicinity of 305 Hz which ought to be the second-order frequency of this thermoacoustic engine. The onset temperature of forced oscillation decreased to 188 °C with the driving frequency of 305 Hz. It also can be observed that in effective frequency range, the closer the driving frequency got to the fundamental or second-order frequency, the lower the onset temperature was. However, onset temperature had no obvious decrease when the driving frequency was far from the fundamental or second-order frequencies, such as 60 Hz, 230 Hz and 400 Hz in this experiment. The impact of driving frequency on damping temperature also shows in Fig. 5. It can be seen that damping temperature almost had the same change trend as onset temperature. It decreased in the effective frequency ranges, and reached the minimum value at fundamental frequency. However, the decrease value was very small that less than 3 °C. The temperature of cooler was almost unaffected by different driving frequencies, since it was cooled by 10 °C circulating water during the onset and damping processes.

Theoretically, spontaneous gas oscillation takes place when the temperature difference of heater (T_h) and cooler (T_c) exceeds the

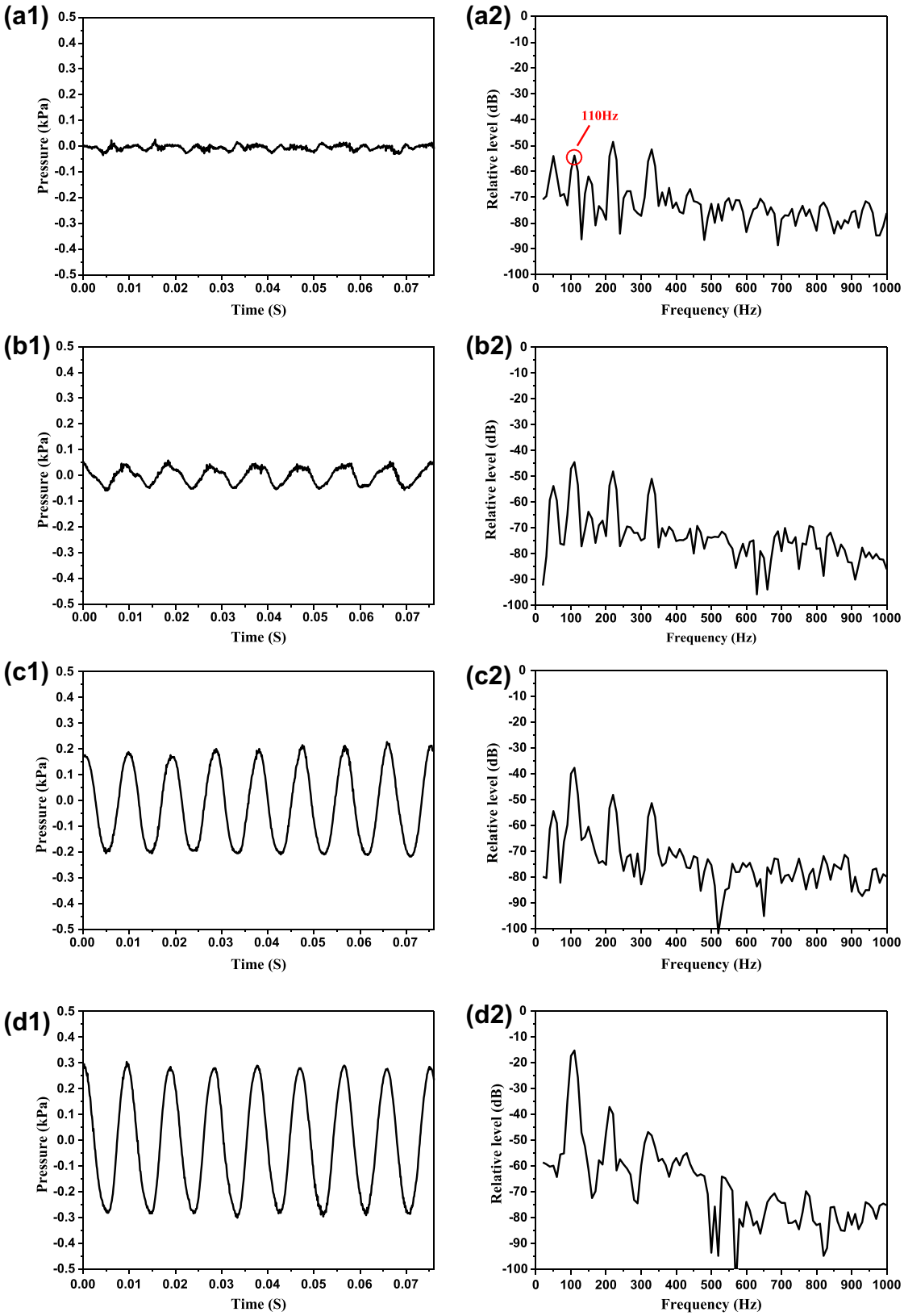

Fig. 6. Pressure and frequency spectrum changes in forced onset process with 110 Hz.

critical temperature gradient ∇T_{crit} of thermoacoustic engine [27]. While in practice, it needs a higher temperature difference to onset since the viscous resistance in the resonance tube is unavoidable. The driving sound with appropriate frequency provides an additional driving force to the system. It effectively overcomes the viscous resistance and makes the thermoacoustic engine onset in advance when the temperature difference exceeds the critical temperature gradient. Once onset, it just needs a lower temperature difference to sustain the oscillation. In the damping process, the amplitude gradually decreases with the decrease of tempera-

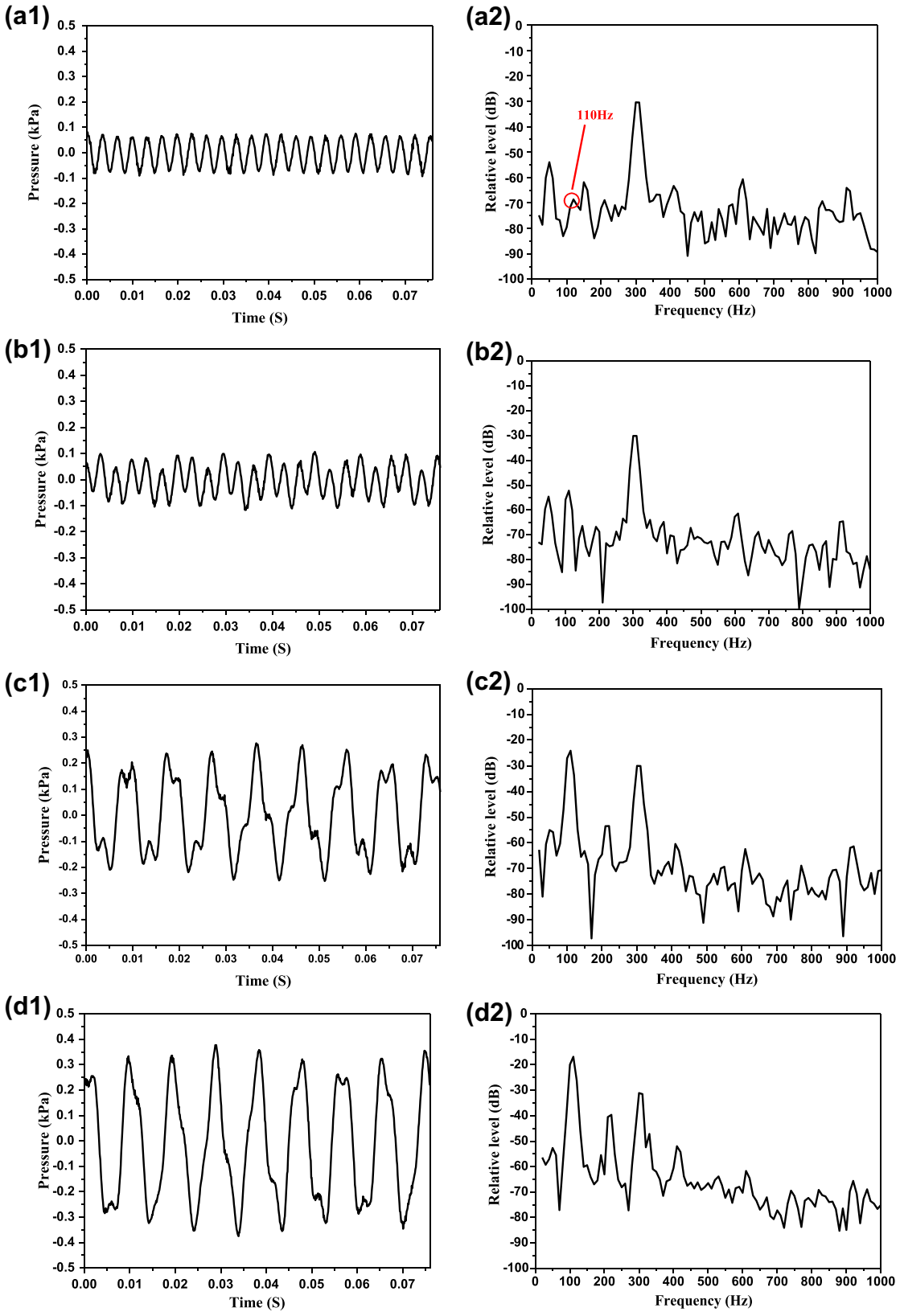

Fig. 7. Pressure and frequency spectrum changes in forced onset process with 305 Hz.

ture. The viscous resistance in resonance tube still makes the damping temperature higher than the critical temperature. The existence of external driving force overcomes the viscous resistance and makes the damping temperature have a slight decrease. Since the impact on damping temperature is very weak, from the view of energy conservation, the loudspeaker can be removed after system onset in practical application.

The selectivity for driving frequency can be explained through the frequency spectrum analysis during onset process. The changes of pressure oscillation and frequency spectrum with driving fre-

quency of 110 Hz are shown in Fig. 6. It can be seen from Fig. 6a that a weak multi-frequency pressure oscillation existed in the resonance tube before onset. The frequency mainly distributed at mains frequency 50 Hz, driving frequency 110 Hz and its double and treble frequencies. When the gas oscillation took place in Fig. 6b and c, pressure waveform of 110 Hz quickly generated and grew up. In the frequency spectrogram, the proportion of 110 Hz gradually increased and it finally became the main frequency. When oscillation stabilized, the pressure amplitude reached 0.3 kPa in Fig. 6d1. Higher harmonic can also be found in frequency spectrogram with a relatively low proportion, as shown in Fig. 6d2. Compare with the self-excited oscillation, the forced oscillation with 110 Hz driving frequency is easy to onset. Since the onset process of forced oscillation does not need the frequency selection stage but just amplifies the pressure wave of 110 Hz.

With the driving frequency of 305 Hz, the onset process of forced oscillation is different with that of 110 Hz and self-excited oscillation. The pressure change and frequency spectrum analysis are shown in Fig. 7. It can be seen from Fig. 7a that pressure oscillation with frequency of 305 Hz played the dominant role before onset. In the frequency spectrogram, frequency of 110 Hz existed before onset but only with a small proportion. With the onset of thermoacoustic engine, the proportion of 110 Hz quickly increased. The pressure waveform became a composite wave of 110 Hz and 305 Hz in Fig. 7b and c. When the oscillation stabilized, 110 Hz became the main frequency in the system. Meanwhile, oscillation with 305 Hz also existed and had a significant influence on the waveform as shown in Fig. 7d. It can be concluded that thermoacoustic engine can onset in advance with the driving frequency of 305 Hz which is the second-order frequency of system. However, the existed harmonic with the driving frequency of 305 Hz reduces the system efficiency and goes against utilization. Therefore, in practical application, the frequency of self-excited oscillation (fundamental frequency) is the best choice to drive the forced oscillation which cannot only effectively decrease the onset temperature but also do not cause the harmonic.

It can be noticed from the above pressure waveforms that the pressure amplitudes of self-excited oscillation and forced oscillation after onset have big difference. To investigate the effect of driving frequency on amplitude, pressure amplitude of forced oscillation with different driving frequencies was studied and the results are show in Fig. 8. Similarly, the amplitude point with the driving frequency of 0 Hz represents the pressure amplitude of self-excited oscillation. It can be seen from Fig. 8 that the change trend of amplitude with different driving frequencies is similar to that of onset temperature in Fig. 5. Forced oscillation had the lowest pressure amplitude with the driving frequency of 110 Hz where it also had the lowest onset temperature. In the effective frequency range, the amplitude was lower than that of the self-excited oscillation. And the closer driving frequency got to the fundamental frequency, the smaller the amplitude was. The second-lowest amplitude appeared with the driving frequency of 305 Hz where system also had the second-lowest onset temperature. It can be concluded that pressure amplitude of forced oscillation is mainly decided by the onset temperature. Pressure amplitude as an important physical parameter shows the intensity of acoustic oscillation. In the thermoacoustic engine, acoustic energy is converted by heat and its intensity is decided by the working temperature. Therefore, forced oscillation with lower onset temperature has smaller pressure amplitude than that of self-excited oscillation. This phenomenon meets the law of energy conversion. The lower the onset temperature is, the smaller the pressure amplitude is.

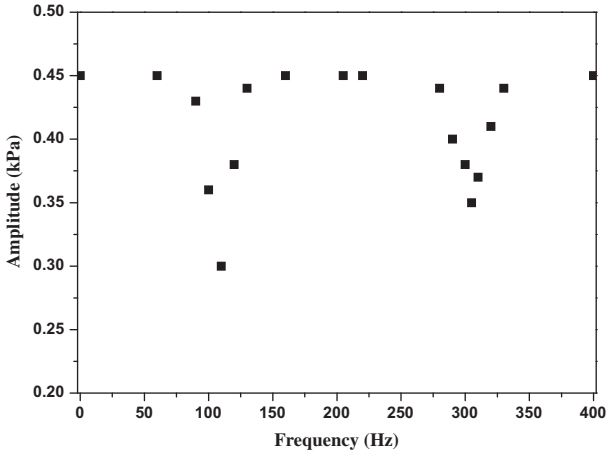

Fig. 8. Pressure amplitude with different driving frequencies.

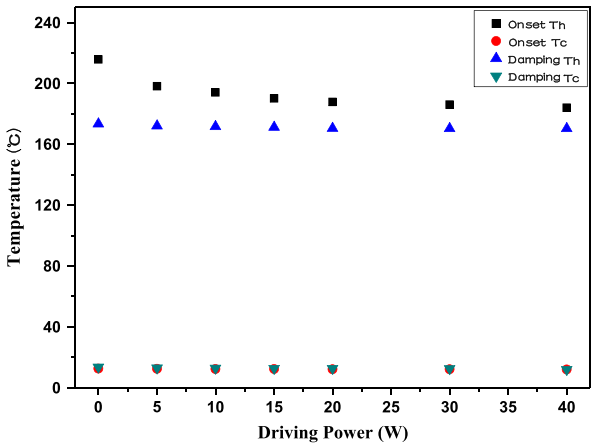

Fig. 9. Onset and damping temperatures with different driving powers.

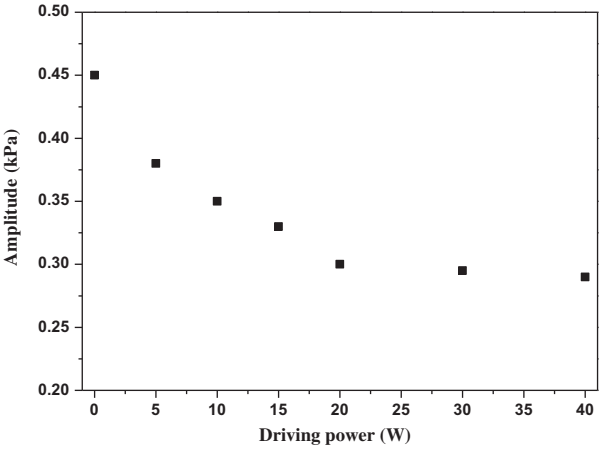

Fig. 10. Pressure amplitude with different driving powers.

3.3. Forced thermoacoustic oscillation with different driving powers

Effect of different driving powers on the onset and damping temperatures is shown in Fig. 9. The driving frequency was 110 Hz in this experiment. Temperature point at 0 W represents the situation of self-excited oscillation. It can be seen from Fig. 9 that onset temperature decreased with the addition and increase of driving power in the beginning. It decreased from 215.7 °C to 198 °C with the addition of 5 W driving power and decreased to 187.5 °C when the driving power increased to 20 W. However, onset temperature had no obvious change when the driving power

continually increased from 20 W to 40 W. In summary, the onset temperature can only decrease to a certain value with the increase of driving power. The further increase of driving power does not work when the lowest onset temperature is achieved. As the analysis above about the impact of driving frequency, external driving force can overcome the viscous resistance in the resonance tube and make the thermoacoustic engine onset in advance when the temperature difference exceeds the critical temperature gradient. Stronger driving force can overcome the effect of viscous resistance more effectively. However, each thermoacoustic engine has a lowest onset temperature. The increase of driving power cannot decrease the onset temperature any more when it achieved the lowest value. This inference was also proposed by Qiu et al. [22] and it was validated in this experiment. It is worth noting that the lowest onset temperature is still higher than the damping temperature about 17 °C, since the onset process always need higher temperature difference to drive.

The pressure amplitude of forced oscillation with different driving powers is shown in Fig. 10. Similar to its influence on onset temperature, the amplitude decreased with the increase of driving power. It decreased from 0.45 kPa to 0.38 kPa with the addition of 5 W driving power and decreased to 0.3 kPa when the driving power increased to 20 W. However, pressure amplitude had no significant change when the driving power continually increased from 20 W to 40 W. Pressure amplitude as a parameter to describe the oscillation intensity is affected by the onset temperature. With the increase of driving power, the onset temperature gradually decreases to the lowest value and the amplitude of pressure oscillation weakens.

4. Conclusions

For the better application of thermoacoustic engine in low grade thermal energy, loudspeaker was used to drive the thermoacoustic engine to decrease its onset temperature. The onset process of forced oscillation driven by loudspeaker was studied comparing with that of self-excited oscillation. In order to provide a guide for the selection of driving signal in practical application, effects of driving frequency and power on the onset temperature and pressure amplitude were investigated. Several useful results were concluded as follows:

1. Forced oscillation driven by loudspeaker is an effective method to decrease the onset temperature of thermoacoustic engine. However, it has higher selectivity for the driving frequency. Only the driving frequency in effective range can decrease the onset temperature of thermoacoustic engine.
2. The self-excited oscillation frequency (fundamental frequency) and second-order frequency are the most effective driving frequencies to decrease the onset temperature of thermoacoustic engine. However, the pressure waveform was significant influenced by the harmonic when driven by second-order frequency. Therefore, the self-excited oscillation frequency (fundamental frequency) is the optimal choice to drive the thermoacoustic engine in practical application.
3. Onset temperature decreases with the increase of driving power in the beginning and then it tends to be constant when the lowest onset temperature is achieved. The lowest onset temperature of forced thermoacoustic oscillation is 187.5 °C in this experiment.
4. Pressure amplitude of forced oscillation is mainly affected by the onset temperature. The lower the onset temperature is, the smaller the pressure amplitude is.

Acknowledgements

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